Kaon-Nucleus Drell-Yan Processes and Kaon Structure Functions

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Abstract

We investigate the information which could be obtained from Drell-Yan processes with sufficiently intense beams of charged kaons on isoscalar targets. It is found that combinations of K^+ and K^- Drell-Yan measurements on isoscalar nuclear targets would allow one to extract the kaon sea quark distributions. These cross sections are also sensitive to the strange valence quark distribution in the kaon, although one would need a significant increase over the presently available kaon fluxes in order to extract this quantity with sufficient accuracy.

PACS: 13.60.Hb; 12.40.Gg; 12.40.Vv.

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1

In principle, the Drell-Yan [DY] process allows one to separate the valence and sea quark distributions for nucleons. One can also obtain meson structure functions by using a combination of Drell-Yan processes and prompt photon data [1-6]. Existing measurements give reasonable constraints on pion valence quark distributions, although the lack of sufficient data at small x_π does not allow the pion sea quark distribution to be extracted. In a previous letter [7] we showed that a comparison of Drell-Yan processes induced by oppositely charged pions on an isoscalar target would allow one to determine the pion sea quark distribution unambiguously.

Given a sufficiently intense beam of kaons, one could repeat these measurements to extract information on the parton distributions in the kaon. Amongst the many questions of theoretical interest which could be addressed we mention the difference in the valence distributions of the strange and non-strange quarks in the kaon, and the possibility of comparing valence distributions in the kaon and pion. In addition, at the present time there is no information at all on the quark sea in the kaon. Our aim is to derive the relevant Drell-Yan cross sections and investigate their sensitivity to these aspects of the structure of the kaon.

In the Drell-Yan process [8], a quark (antiquark) of a certain flavor in the projectile annihilates an antiquark (quark) of the same flavor in the target, producing a virtual photon which later decays into a $\mu^+ - \mu^-$ pair. For nucleon-nucleus events, the antiquark is necessarily part of the sea, so all Drell-Yan events involve at least one sea quark. Since a kaon has one valence quark and one valence antiquark, various combinations of valence and sea quarks are possible for kaon-nucleus Drell-Yan processes. Combinations of positively and negatively charged kaons on isoscalar targets allow the valence-valence interactions to be separated in a straightforward way.

Assuming, for illustrative purposes, a deuteron [D] target, the Drell-Yan cross sections for positive and negative kaons have the form

$$
\begin{aligned}
\sigma_{DY}^{K^+D}(x, x_K) &= \frac{2}{9}\left[4u_{\mathrm{v}}^{K^+}(x_K) + \kappa\bar{s}_{\mathrm{v}}^{K^+}(x_K) + (10 + 2\kappa)q_{\mathrm{s}}^{K}(x_K)\right]q_{\mathrm{s}}^{N}(x) \\
&+ \frac{10}{9}q_{\mathrm{s}}^{K}(x_K)q_{\mathrm{v}}^{N}(x), \\
\sigma_{DY}^{K^-D}(x, x_K) &= \frac{2}{9}\left[4\bar{u}_{\mathrm{v}}^{K^-}(x_K) + \kappa s_{\mathrm{v}}^{K}(x_K) + (10 + 2\kappa)q_{\mathrm{s}}^{K}(x_K)\right]q_{\mathrm{s}}^{N}(x)
\end{aligned}
$$

$$+ \left[\frac{8}{9} \bar{u}_{\text{v}}^{K^-}(x_K) + \frac{10}{9} q_{\text{s}}^K(x_K) \right] q_{\text{v}}^N(x). \tag{1}$$

In Eq. 1 we assumed the validity of charge symmetry, i.e. $d^n(x) = u^p(x)$, $u^n(x) = d^p(x)$, etc. While there have been predictions of significant charge symmetry violation in the parton distributions of the nucleon [9, 10], and the Drell-Yan process may be extremely useful in testing those predictions [7, 11], any reasonable deviation from charge symmetry would have a negligible effect on the reactions considered here. Assuming charge symmetry we can write all processes in terms of parton distributions in the proton, where we defined the valence distribution $q_{\text{v}}^N(x) \equiv (u_{\text{v}}^p(x) + d_{\text{v}}^p(x))/2$. In addition, for the kaon sea we assumed SU(3) symmetry – i.e. we assumed the up, down and strange quark sea distributions in the kaon to be equal ($u_{\text{s}}^K = d_{\text{s}}^K = s_{\text{s}}^K \equiv q_{\text{s}}^K$) – since no other information is available on the kaon sea. Finally, for the nucleon we assumed $q_{\text{s}}^N(x) \equiv (u_{\text{s}}(x) + d_{\text{s}}(x))/2 = s(x)/\kappa$, where the fraction κ of the strange sea is chosen to reproduce the experimental ratio of dimuon events to single-muon events in neutrino-induced reactions [12, 13, 14] at the scale $Q^2 = Q_0^2 = 4$ GeV^2. Under these assumptions, K^+ and K^- DY processes on isoscalar targets should produce identical cross sections, except for the additional contribution in the K^- case which is proportional to the product of the $\bar{u}$ valence quark in the kaon times the up quark distributions in the proton and neutron. Consequently, if we form the linear combination

$$\Sigma_{\text{v}}^{KD}(x, x_K) = \sigma_{DY}^{K^-D} - \sigma_{DY}^{K^+D} = \frac{8}{9} \bar{u}_{\text{v}}^{K^-}(x_K) q_{\text{v}}^N(x), \tag{2}$$

the K^+D DY cross section contains no valence-valence contribution (it contains only sea-valence and sea-sea terms), while Σ_{v}^{KD} contains only a valence-valence term (note that our equations are correct for any isoscalar nuclear target; however, the quantity $q_{\text{v}}^N(x)$ would then be the nuclear valence quark distribution function. To extract the free nucleon quark distribution one would have to understand binding and EMC-type nuclear corrections to the quark distributions).

This means that if one measures K^+ and K^- Drell-Yan cross sections on an isoscalar nucleus, then the K^+D cross sections are sensitive to sea-valence and sea-sea interference terms, whereas the valence-valence contribution can be obtained from $\Sigma_{\text{v}}^{KD} = \sigma_{DY}^{K^-D} - \sigma_{DY}^{K^+D}$. Furthermore, since the quantity Σ_{v}^{KD} separates in the variables x and x_K, the up quark valence distribution

in the kaon can be obtained by integrating this quantity over all x, i.e.

$$\bar{u}_{\rm v}^{K^-}(x_K) \;\; = \;\; \frac{3}{4} \int_0^1 \Sigma_{\rm v}^{KD}(x, x_K)\, dx \quad .$$ (3)

As a consequence, it may be possible to obtain the nonstrange valence quark distribution in the kaon even with reasonably low kaon fluxes.

If one defines the sea-to-valence ratios for kaon and nucleon,

$$
\begin{aligned}
r_{\rm s/v}^{N}(x) &\equiv [u_{\rm s}^{p}(x) + d_{\rm s}^{p}(x)]/[u_{\rm v}^{p}(x) + d_{\rm v}^{p}(x)], \\
q_{\rm s/v}^{K}(x) &\equiv q_{\rm s}^{K}(x)/u_{\rm v}^{K}(x), \\
R_{\rm s/u}^{K}(x) &\equiv s_{\rm v}^{K}(x)/u_{\rm v}^{K}(x), .
\end{aligned}
$$ (4)

we find the following ratio

$$
\begin{aligned}
R_{\rm s/v}^{K}(x, x_K) &\equiv \sigma_{DY}^{K^+D}/\Sigma_{\rm v}^{KD} \\
&= \frac{5}{4} q_{\rm s/v}^{K}(x_K) + r_{\rm s/v}^{N}(x)\left[1 + \frac{5+\kappa}{2}\, q_{\rm s/v}^{K}(x_K) + \frac{\kappa}{4}\, R_{\rm s/u}^{K}(x_K)\right]
\end{aligned}
$$ (5)

Measuring these cross sections requires a sufficiently intense and reasonably pure kaon beam. With the FNAL MI upgrade and a dedicated kaon beam line, one could envision substantial improvement in kaon flux, but this may still be below the rates necessary to get precision DY measurements.

To estimate the magnitudes of expected DY ratios, we used kaon valence quark structure functions from Shigetani, Suzuki and Toki [15]. They used a Nambu-Jona Lasinio [NJL] model to generate the valence quark distributions. These structure functions were able to reproduce the CERN NA3 measurements of Badier et al. [6], who compared kaon and pion-induced DY cross sections. They showed that at large x for the meson, the up quark structure function in the kaon was substantially smaller than that for the pion. This was expected since the heavier s quark of the kaon should carry more of the momentum than the lighter nonstrange quark.

In Fig. 1, we show the predicted valence quark distributions for the kaon. The dotted curve is the quark distribution at the hadronic scale $Q_0^2 = (0.5\ {\rm GeV})^2$, while the solid curve is the valence distribution evolved to $Q^2 = 20\ {\rm GeV}^2$. From Fig. 1b, we see that the strange

quark distribution is substantially bigger than the nonstrange quark distribution at large x_K, in agreement with the experimental measurements of Badier et al. [6]. Since we know of no sea quark distributions for the kaon, we used the phenomenological sea quark distributions for the pion from Sutton et al. [1, 16]. The nucleon quark distributions were the CTEQ(3M) fits from the CTEQ collaboration [17]. All of these were calculated for $Q^2 = 20$ GeV^2.

In Fig. 2 we show the quantity $\Sigma_{\rm v}^{KD}$ versus x_K for various values of nucleon x. As was discussed previously, this function separates in x and x_K, so that if we integrate $\Sigma_{\rm v}^{KD}(x, x_K)$ over all x we can extract the up quark valence distribution in the kaon. The NJL distributions of Shigetani et al. fall off monotonically in x_K for fixed x.

In Figs. 3 we show predictions for $R_{\rm s/v}$ (the ratio of σ_{DY}^{K+D} to $\Sigma_{\rm v}^{KD}$, defined in Eq. 5), versus x_K, for three values of nucleon momentum fraction ($x = 0.2$, 0.3 and 0.4). At each value of x, we show curves corresponding to four different kaon sea quark distributions; these are taken from the pion sea quark distributions of Sutton et al. [1]. Those correspond to different fits to the NA10 Drell-Yan data [2, 3], where the meson sea carries from 5% to 20% of the pion's momentum at $Q^2 = 20$ GeV^2 (i.e., these are fits $2 - 5$ of Ref. [1]). The predicted ratio $R_{\rm s/v}^K$ is quite large: e.g., for $x = x_K = 0.2$, $R_{\rm s/v}^K$ varies from around 0.2 to 0.5 depending on the momentum fraction carried by the sea. Furthermore, $R_{\rm s/v}^K$ is quite sensitive to the momentum fraction carried by the sea. The quantity $R_{\rm s/v}^K$ is more or less linear in this momentum fraction; the difference between a parton distribution where 5% of the kaon's momentum is carried by the sea, and one where 20% of the momentum is carried by sea quarks, is roughly a factor of 3 in $R_{\rm s/v}^K$.

Thus, assuming the availability of sufficiently intense separated beams of kaons, even qualitative measurements of $R_{\rm s/v}^K$ would be able to differentiate between kaon parton distributions where the sea carries different fractions of the kaon's momentum. The process could be measured at relatively small values of x and x_K provided that sufficiently large count rates of muon pairs could be obtained.

One remaining quantity is the kaon's strange quark valence distribution. In Eq. 5 this arises from annihilation between a strange valence quark in the kaon and the strange sea of the

nucleon. At large x_K, the strange quark in the kaon should carry more of the kaon's momentum than the nonstrange quark, due to the larger mass of the strange quark. This was confirmed in the NA3 measurements of Badier et al. [6], which showed that the $\bar{u}$ distribution in the K^- was roughly half the $\bar{u}$ distribution in the π^- at large x, as measured in meson-nucleus Drell-Yan processes. This large-x depletion of the nonstrange valence distribution in the kaon is expected to be offset by an increase in the strange quark valence distribution.

In Figs. 4 we show the quantity $R^K_{\mathrm{s/v}}$ versus x_K, for two values of the nucleon momentum fraction ($x = 0.2$ and 0.3). The solid curves include the kaon strange valence quark distribution; in the dashed curves this distribution is set to zero (for illustrative purposes, to show the magnitude of the strange valence contribution). For large x_K, the differences range from 40% at small x ($x \sim 0.2$), to about 15% effects at larger $x \approx 0.4$. However, the quantity $R^K_{\mathrm{s/v}}$ is small in this region, and it would be extremely difficult to extract any information about the kaon's strange valence quark distribution from such measurements. This quantity is relatively small due both to the charge (1/3) of the strange quark, and the strange/nonstrange ratio (κ) of the nucleon sea.

We have assumed the validity of charge symmetry in this work. From previous investigations of charge symmetry violation [CSV] in such systems ([7, 9, 10]) one would expect CSV effects to be at most a few percent in the valence distributions. EMC-type effects ([18]) would also be expected to be small for light isoscalar targets.

In conclusion, with presently available kaon beams precision Drell-Yan experiments are probably not feasible. However, the CERN NA3 group has already been able to obtain Drell-Yan cross sections integrated over x, and to extract qualitative results comparing pion and kaon-induced reactions. It should also be possible for experiments to obtain interesting information on kaon structure at small x and x_K.

References

[1] P.J. Sutton, A.D. Martin, R.G. Roberts and W.J. Stirling, *Phys. Rev.* **D45** (1992) 2349.

[2] NA10 collaboration: P. Bordalo *et al.*, *Phys. Lett.* **B193** (1987) 368.

[3] NA10 collaboration: B. Betev *et al.*, *Z. Phys.* **C28** (1985) 9.

[4] E615 collaboration: J.S. Conway *et al.*, *Phys. Rev.* **D39** (1989) 92.

[5] WA70 collaboration: M. Bonesini *et al.*, *Z. Phys.* **C37** (1988) 535.

[6] NA3 collaboration: J. Badier *et al.*, *Z. Phys.* **C18** (1983) 281.

[7] J.T. Londergan, G.Q. Liu, E. Rodionov and A. W. Thomas, *Phys. Lett.* **B361** (1995) 110.

[8] S.D. Drell, Tung-Mow Yan, *Ann.Phys.* **66** (1971) 578.

[9] E. Rodionov, A. W. Thomas and J. T. Londergan, *Int. J. Mod. Phys. Lett.* **A9** (1994) 1799.

[10] E. Sather, *Phys. Lett.* **B274** (1992) 433.

[11] J.T. Londergan, G.T. Garvey, G.Q. Liu, E. Rodionov and A. W. Thomas, *Phys. Lett.* **B340** (1994) 115.

[12] CCFR collaboration: K. Lang *et al.*, *Phys. Lett.* **B317** (1993) 655; P.Z. Quintas *et al.* *Phys. Rev. Lett.* **71** (1993) 1307.

[13] CCFR collaboration: W. Leung *et al.*, *Z. Phys.* **C33** (1987) 483; H. Rabinowitz *et al.* *Phys. Rev. Lett.* **70** (1993) 134.

[14] CDHSW collaboration: H. Abramowitz *et al.* *Phys. Rev. Lett.* **57** (1986) 298; *Z. Phys.* **C28** (1985) 51.

[15] T. Shigetani, K. Suzuki and H. Toki, *Phys. Lett.* **B308** (1993) 383; Tokyo Metropolitan University preprint TMU-NT940101, 1994, unpublished.

[16] P.N. Harriman, A.D. Martin, W.J. Stirling and R.G. Roberts, *Phys. Rev.* **D42** (1990) 798.

[17] CTEQ collaboration: H.L. Lai, J. Botts, J. Huston, J.G. Morfin, J.F. Owens, J.W. Qiu, W.K. Tung and H. Weerts, preprint HEP-PH-9410404, unpublished.

[18] EMC Collaboration (J.J. Aubert *et al.*), *Phys. Lett.* **B123** (1983) 275.

Figure captions

1. Theoretical kaon valence quark distributions, vs. Bjorken x, calculated using the NJL model of Shigetani et al., Ref. [15]. Dotted curve: quark distributions at the hadronic scale, $Q_0^2 = (0.5 \text{ GeV})^2$; solid curve: quark distributions evolved to $Q^2 = 20 \text{ GeV}^2$. (a) up quark valence distribution in the kaon, $x\, u_{\rm v}^K(x)$; (b) strange quark valence distribution in the kaon, $x\, s_{\rm v}^K(x)$.

2. Predicted valence quark distributions for kaon-nucleus reactions on isoscalar targets. The quantity $\Sigma_{\rm v}^{KD}$ of Eq. (2) is plotted vs. x_K for four different values of nucleon momentum fraction x. Solid curve: $x = 0.6$; dashed curve: $x = 0.4$; long-dashed curve: $x = 0.3$; dot-dashed curve: $x = 0.2$. Nucleon parton distributions are CTEQ(3M) parameterization of Ref. [17]; kaon valence distributions are those of Shigetani et al., Ref. [15].

3. Predicted sea/valence term $R_{\rm s/v}^K$ of Eq. 5, vs. the kaon momentum fraction x_K, for various kaon sea quark distributions, which vary according to the fraction of the kaon's momentum carried by the kaon sea. Solid curve: kaon sea carries 20% of the kaon's momentum; dashed curve: kaon sea of 15%; long-dashed curve: kaon sea of 10%; dot-dashed curve: kaon sea of 5%. (a) Nucleon momentum fraction $x = 0.2$; (b) $x = 0.3$; (c) $x = 0.4$. Valence parton distributions are those of Fig. 1. Meson sea quark distributions are pion sea quark distributions of Sutton et al., Ref. [1].

4. Dependence of sea/valence ratio $R_{\rm s/v}^K$ on the strange valence distribution of the kaon, plotted v. kaon momentum fraction x_K. Solid curve: the quantity $R_{\rm s/v}^K$ of Eq. 5 including the kaon strange valence distribution; dashed curve: the same quantity where the kaon strange valence distribution is set to zero. (a) Nucleon momentum fraction $x = 0.2$; (b) nucleon momentum fraction $x = 0.3$. Nucleon and kaon parton distributions are those of Fig. 2.

(b)

CTEQ(3M)   (a)

kaon sea = 20%
kaon sea = 15%
kaon sea = 10%
kaon sea = 5%

$x_N = 0.2$